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Precursor Missions to Interstellar Exploration[1]

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Abstract - This paper summarizes material developed over a three-month period by a JPL team of mission architects/analysts and advanced technology developers for presentation to NASA Headquarters in the summer of 1998. A preliminary mission roadmap is suggested that leads to the exploration of star systems within 40 light years of our Solar System. The precursor missions include technology demonstrations as well as missions that return significant new knowledge about the space environment reached. Three propulsion technology candidates are selected on the basis of allowing eventual travel to the nearest star taking 10 years. One of the three propulsion technologies has a near term version applicable to early missions (prior to 2010) - the solar sail. Using early sail missions other critical supporting technologies can be developed that will later enable Interstellar travel. Example precursor missions are sail demonstration missions, including a solar storm warning mission demonstrating a simple sail, a solar polar imaging mission using an intermediate sail, and a 200-AU Heliosphere Explorer mission using an advanced solar sail. Missions later than these on the roadmap will require types of fusion propulsion, antimatter-matter annihilation propulsion, or enhancements to the sail technology to propel spacecraft to the stars in the relatively short trip times desired. The sail enhancement envisioned at this time uses an Earth-based laser in what is termed as a beamed-energy approach. Mission and technology strategy, science return, and potential mission spin-offs are described.

space mission

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1. INTRODUCTION

Technology advances in the space exploration arena appear to be accelerating at a rate difficult to have predicted only a short time ago. Our vision of missions that might be have often fallen behind what could be. This paper suggests that Interstellar Exploration is a vision that can provide a mission and technology roadmap worthy of the pace that new technology concepts and ideas are now becoming reality.

Described in this paper is a summary of material developed over a three-month period by a JPL team of mission architects/analysts and advanced technology developers for presentation to NASA Headquarters in the summer of 1998. The initial hypothesis for the effort was that a far-reaching program like Interstellar Exploration would provide an exciting goal relevant to all of NASA's space science themes, as well as flex the mental muscles of our mission designers and technologists, leading them to think in terms of the far future and how needs then might affect the performance and requirements of our nearer term programs.

The initial vision of flight to any star within 40-light years taking less than 100 years set the key propulsion technology goal and led to a set of propulsion options for study. On the basis of energy capability the propulsion candidates were downselected to three potential propulsion technologies that might ultimately meet the vision goal: beamed energy, fusion, and matter-antimatter. Each of these options carries with it technology hurdles that will need to be overcome; some of these hurdles are very difficult, and it is not clear today how they might be cleared. The preliminary mission/technology roadmap suggested in this paper does tie to the Interstellar vision, focusing on near term steps that are clearer in implementation and technology requirements. The beamed energy propulsion option was selected to initiate early technology demonstration missions because its solar sail, the basis for beamed energy, has a near-term technology roadmap that is relatively clear compared to the other two options.

Travel to the stars has been the stuff of science fiction as long as there has been science fiction. Serious thinking in the last half of this century to test the credibility of the

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concept has produced a number of creative ideas. Three papers, one almost 40 years old, are classic references - [1-3]. Reference [4] is one of the most recent and comprehensive papers on the evaluation of propulsion technology for eventual use in Interstellar Exploration. Our current paper sets a vision goal for Interstellar Exploration, complementary to other NASA Space Science Program goals. Given the ultimate vision of stellar exploration, a preliminary roadmap is suggested that lists several precursor missions along the way. Examples of these missions are described in the context of the suggested Interstellar Exploration roadmap.

2. INTERSTELLAR EXPLORATION

NASA Strategic Plan

NASA has embarked on a Strategic Plan for which Space Science is an integral part. The Space Science Directives that come out of the NASA Strategic Plan are [5]:

- Solve Mysteries of the Universe
- Explore the Solar System
- Discover Planets Around Other Stars
- Search for Life Beyond Earth

These Directives relate to all four of the major NASA Space Science Themes: Solar System Exploration (SSE), Sun-Earth Connection (SEC), Structure and Evolution of the Universe (SEU), and Origins. An appropriate Interstellar Exploration vision will be complementary and synergistic with the NASA Space Science Directives and Themes.

Interstellar Exploration Vision

Let us first look at the Origins initiative which has a vision with a roadmap of three generations of missions. The first two generations last about a decade each. First Generation Missions image first-galaxies and star formations in the first decade of the new century. The 2nd Generation Missions will catalog the habitable planets of the nearest 1000 stars (out to 40 light years). The 3rd Generation Missions plan to image planets around other stars. The three other Space Science themes automatically benefit from Interstellar Exploration, either directly or through technology spin-offs.

Given the Origins vision we suggest an Interstellar Exploration vision or goal of reaching any of the habitable planets discovered by the Origins Program, and reach the farthest targets in less than one century.

Propulsion Technology

Technology advances for such a difficult endeavor are not easy. In the case of the propulsion technology, we are not sure today what the ultimate propulsion system will look like. A broad set of possible candidates was evaluated in [5]. The following chart, Figure 1, summarizes the performance capabilities studied in [5].

The Interstellar Exploration vision we suggest requires an average cruise speed near 0.5 times the speed of light. This speed would allow travel to the nearest star, Alpha Centauri, taking less than 10 years, and to the far reaches of our stellar neighborhood (out to 40 light years) taking less than 100 years. We see from Figure 1 that only three propulsion technologies have the potential for meeting our vision: beamed energy (solar sail with Earth-based laser), fusion ramjet, matter-antimatter annihilation.

Of these three, beamed energy will allow the earliest tests of technologies that will need to be developed along the path to Interstellar Exploration. In fact solar sails can implement a vigorous test of other technologies and allow early implementation of the Interstellar Exploration roadmap. Early missions - precursor missions - will be enabled that achieve not only advanced technology development and demonstrations, but also achieve significant milestones in NASA's Space Science Mission Program.

Although an early use of beamed energy is suggested, this by no means implies ultimate selection for use in missions to the stars. Fusion ramjet and matter-antimatter annihilation concepts offer the flexibility of in-situ propellant collection or carrying their own fuel and do not depend on a large space-based infrastructure near Earth of beam source and optics systems. On the other hand, we do not yet know how to build, test, and fly early demonstrations of fusion or matter-antimatter rockets. Important research is required and recommended to keep these two options open.

Critical Technologies

Although very advanced propulsion is clearly a requirement for enabling travel in our "stellar neighborhood", other technologies must also be developed that require a similar leap in imagination. These new advances in technology provide a stairway to ever more ambitious missions leading to travel to new star systems.

Other technologies critical to Interstellar Exploration capability, with their preliminary performance thrusts, are listed in Table 1, below:

Table 1 Critical Non-Propulsion Technologies

Technology	Prelim. Performance Thrusts
Communications	5-m antenna/50-W laser on spacecraft; 20-m Earth Orbiting Receiver
Avionics	Quantum/Biological Computing
Power	Energy Storage @ 1 kW-hr/kg; 100-kW Nuclear Auxiliary Power
Structures	In-Space Fabrication & Assembly; Thin Films (0.1 g/m^2); Large Space Structures
Autonomy	Surprise-able, Self-Diagnostic, and Self-Repairable Systems
Navigation	Self-Determination of Ephemerides and Exploration Strategies

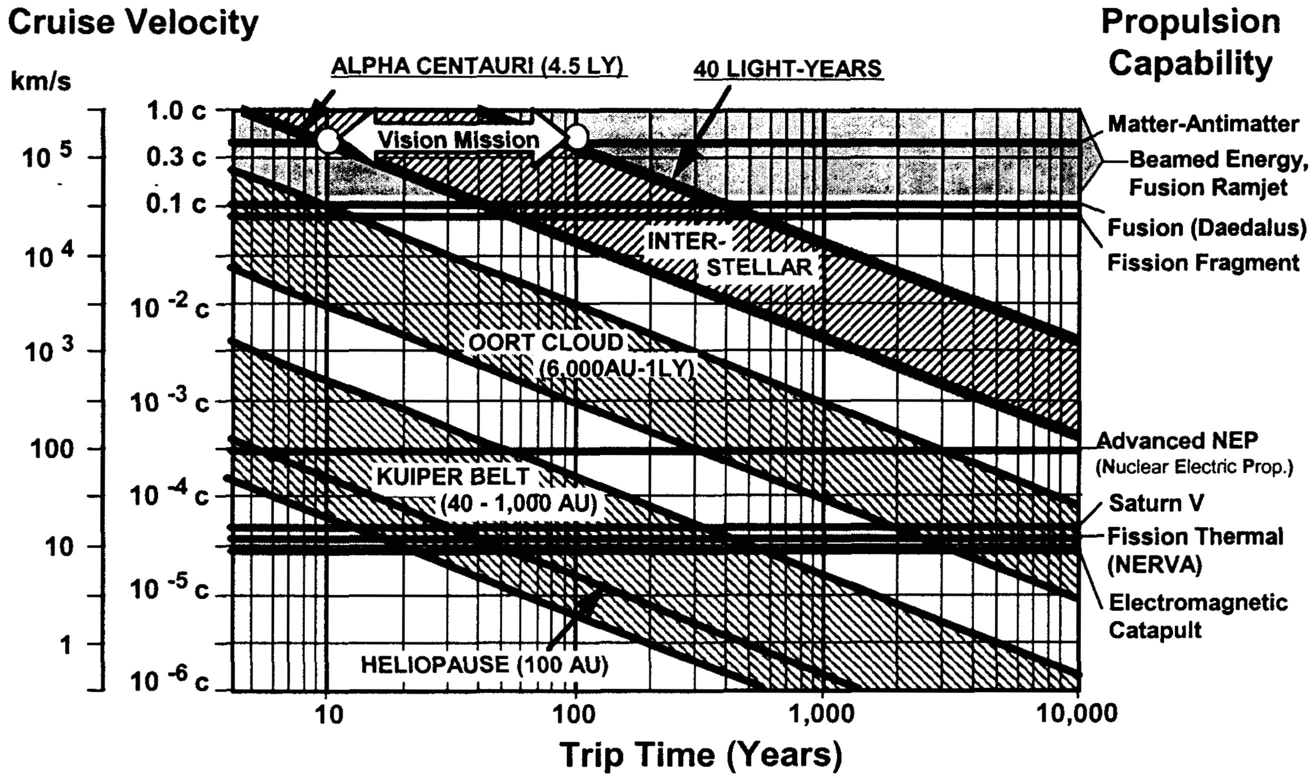

Figure 1. Propulsion Candidates, Cruise Speed, and Trip Times (After Frisbee/Leifer, [5])

3. PRELIMINARY ROADMAP

Figure 2 is a preliminary Mission and Technologies Roadmap for Interstellar Exploration. Three generations of technologies and missions are suggested.

The First Generation takes us to an important decision point, selection of the propulsion concept to carry us forward on the roadmap. Our estimate is that this selection will be possible at the end of the first decade of the new millennium. Many of the critical technologies can be demonstrated by then on advanced sail-based missions that will explore the interstellar medium out to 200 to 300 AU. Beyond 2010 our understanding of the technology needs for stellar fly-through missions is speculative, and so we don't have an estimate of when the beginning of missions with long stays at neighboring stars would occur.

Solar Sail technology is the primary propulsion for technology demonstration missions in the First Generation of our Preliminary Roadmap because we better understand how to implement these early missions with this technology than with the other two advanced propulsion candidates. Their technology development will proceed in parallel with the other technology developments.

Our preliminary roadmap is a precursor roadmap to the one that will continue to evolve as we move forward. One of the first activities in an Interstellar Exploration Program will be to develop a more detailed schedule of cost and milestones.

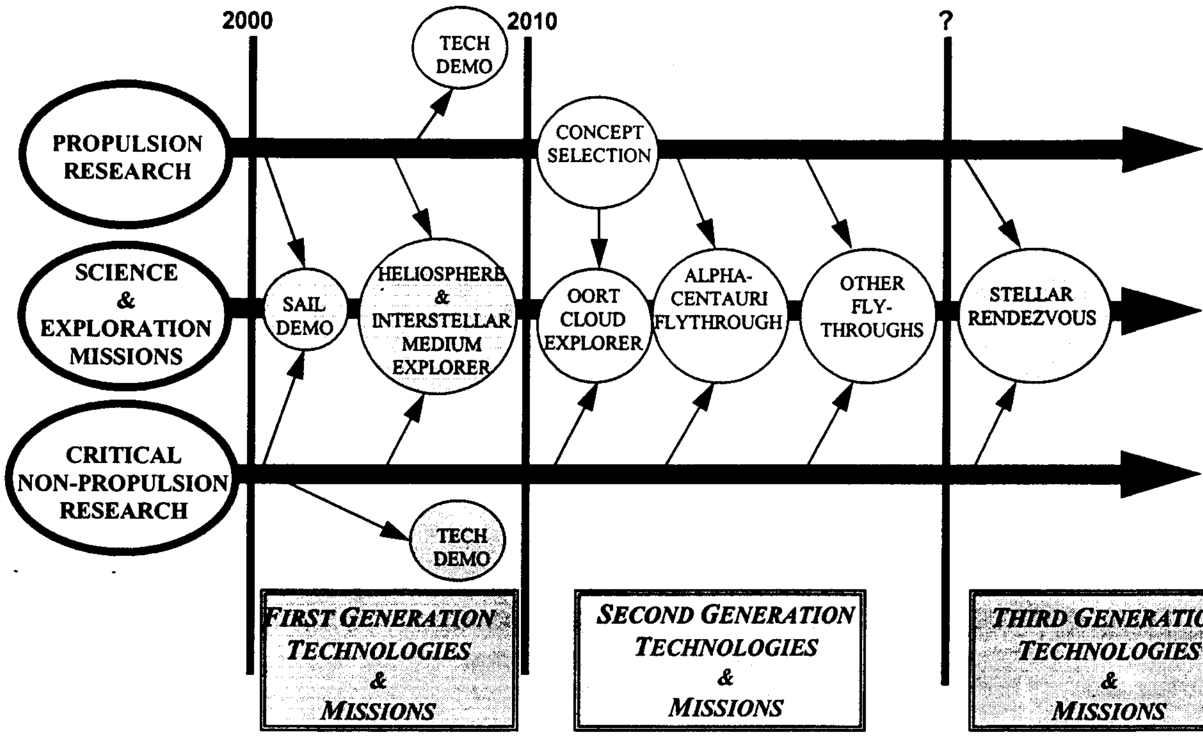

Figure 2. Preliminary Mission and Technologies Roadmap for Interstellar Exploration

4. Precursor Missions

Science Drivers

One of the foundations of our concept of an Interstellar Exploration Program is that it develops not only the technology to eventually reach the stars, but it also returns significant space science in the process. Figure 3 describes in rough terms [6] what the interstellar medium looks like. All items on this chart are exciting targets for exploration.

Sail Roadmap

Early missions in the Preliminary Roadmap will be propelled by solar sails, because of the relatively small advances required in this propulsive technology to achieve the early objectives. A preliminary sail roadmap, with precursor missions, is shown in Figure 4. Relatively primitive sails will need to be demonstrated at the beginning of the roadmap. Near Earth demonstrations are already on the planning boards, and a number of concepts are being suggested for launch. Missions reaching beyond the 200 to 300 AU of the Heliosphere Science mission will require additional energy to keep to the relatively low flight times shown in Figure 4. Very high-energy Earth-based laser power will be required for these later missions. The beamed energy Lightsail concept for interstellar travel has been analyzed by Forward [3] and others. More recently, Frisbee and Leifer [4] include additional technology concepts in the system design and provide a broad-spectrum comparison with other attractive propulsive concepts.

Early Demonstration Missions

The DLR (German Space Agency) has a 40-m design using carbon composite booms. The Russian Space Agency has a design using a spinning structure and plans to demonstrate this sail technology on its continuing series of Znamya missions. The DLR and Znamya sail missions are considered technology demonstration missions with potential for some imaging in the Earth-Moon space.

The Geostorm Warning mission, planning for a launch in the early 2000s, is being developed by JPL. This mission would be a cooperative effort, funded by NASA, NOAA, and the DOD. This mission concept is designed to enable continuous solar wind measurements inwards from the Earth's Sun-Earth Lagrange point (L1 at 0.98 AU). In addition to the Space Physics interest, solar storm warning times are estimated to be double the time for the same instruments placed at L1 (an hour instead of 30 minutes).

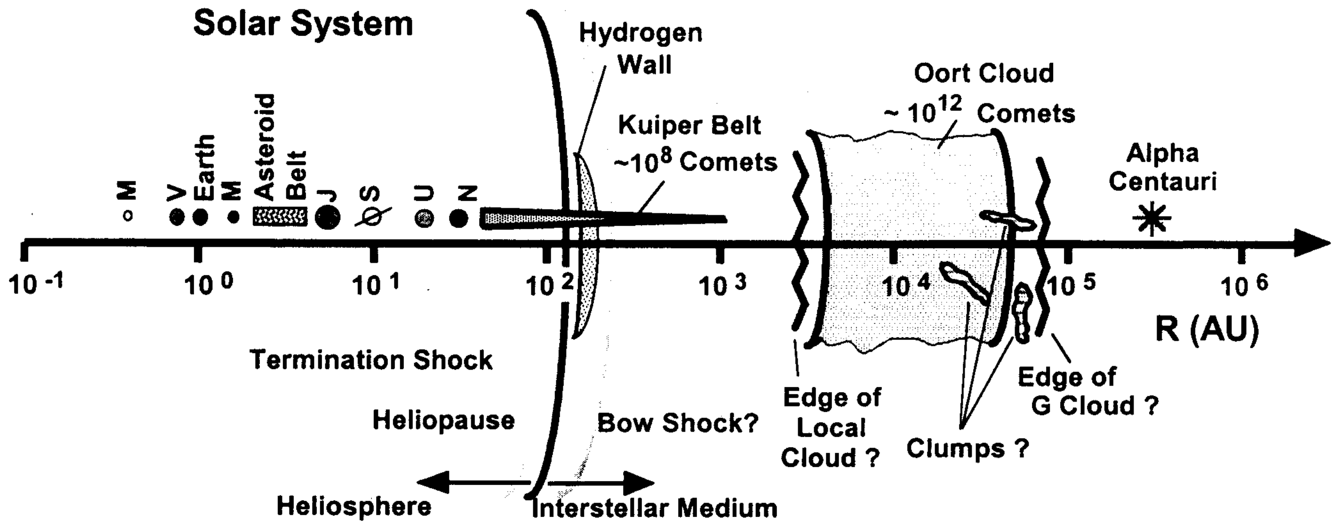

Figure 3. Scale of the Interstellar Medium (After Mewaldt, [6])

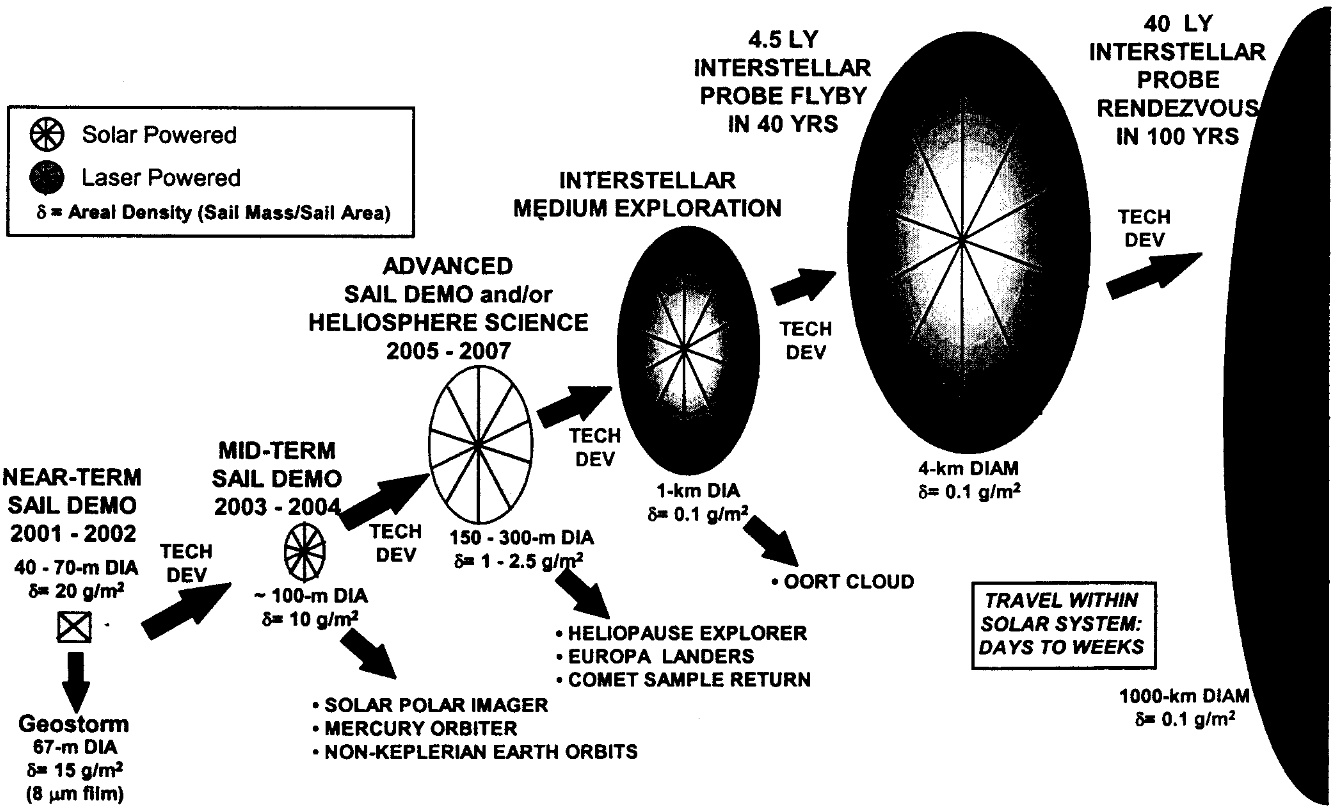

Figure 4. Preliminary Sail Roadmap with Precursor Missions

Early Science Missions Enabled

As sail technology advances, more of NASA's space science missions become enabled. One technology metric for the sail is the areal density (δ), or the mass of the sail and its structural members divided by the area of the sail. As the areal density decreases to the neighborhood of 10 g/m^2, significant continuous acceleration is applied, and a number of Solar System missions of great interest to the Planetary and Space Physics science communities are enabled. See Figure 4. More ambitious missions (more science and shorter trip times, other targets) are possible as the technology advances.

Solar Polar Imager

An example of a science-enabled mission is the Solar Polar Imager. This mission enables studies of the three dimensional structure of the Sun and is in NASA's SEC Strategic Mission Roadmap as one of five Frontier Probes [7]. A JPL study in 1997/98 [8] found a mission/system design solution for the scientific objectives [7] of this mission concept:

- For the first time, view the Sun from high latitudes.
- Discover the sources, longitudinal structure, rotational curvature and time variability of coronal features.
- Image the global extent and dynamic effects of coronal mass ejections.
- Link particle and field observations to images of the Sun, corona and heliosphere at all latitudes.
- Determine magnetic field structures and convection patterns in the Sun's polar regions.
- Follow evolution of solar structures over a full solar rotation or more.

A circular polar orbit 0.48 AU from the Sun was found desirable for the scientific observations. The polar orbit selected is in 3:1 resonance with the Earth, allowing the spacecraft to make a complete orbit around the Sun every 4 months and phased so that the Earth-Sun-spacecraft angle ranges from 30 to 150 deg. Such an orbit arrangement provides a data set on the solar corona that complements observations of the solar disk and solar wind data obtained near Earth. Key to this design was a solar sail with areal density of between 6 and 7 g/m^2. The spacecraft would be launched on a Taurus XL/Star 37 FM in 2005. Other mission options, including both higher and lower sail areal densities, will be studied to understand the science, cost, and schedule trades for this concept.

Heliopause Explorer

Like the Solar Polar Imager the Heliopause Explorer is one of five Frontier Probe missions in the SEC Strategic Mission Roadmap [7]. This mission is also a key mission on our Preliminary Interstellar Exploration roadmap (see Figures 2, 3, and 4).

The science objectives for this mission are taken from [6]:

- Explore the nature of the interstellar medium and its implication for the origin and evolution of matter in the Galaxy:
  - Pressure and energy balance of the interstellar medium; mechanisms for ionization, heating, and dynamics of interstellar gas
  - Chemical evolution of galaxy; origin of solar system; nucleosynthesis
- Explore the structure of the heliosphere and interaction with the interstellar medium:
  - Termination shock location, motion, and structure
  - Heliopause structure, bow shock, and penetration of gas and dust
- Explore fundamental astrophysical processes occurring in heliosphere and interstellar medium:
  - Shock acceleration of anomalous cosmic rays and other species
  - Turning of the subsonic solar wind and the interstellar plasma flows

A mission concept has been developed for launch in 2008. Trajectory options are designed to reach 200 AU between 10 and 20 years after launch, depending on technology advances in sail and spacecraft miniaturization (please see further discussion below). A science payload was recommended in a 1990 Interstellar Probe Workshop [9]. This science payload was recently confirmed in [6], although instrument advances have allowed considerable reduction in mass requirements from the original 125 kg (see Table 2).

Table 2 Heliopause Explorer Science Payload

<u>SCIENCE PAYLOAD: (kg, W)</u>

- Magnetometer (1, 0.5)
- Plasma Waves; Radio (3, 3)
- Neutral H, He, O; Energetic Neutral Atoms; Interstellar Plasma Ions (3, 3)
- Interstellar Solar Wind Electrons; Interstellar Plasma Mass/Charge; Composition, Suprathermal & Pickup Ions (4, 4)
- Anomalous/Galactic Cosmic Ray Isotopes (3, 2)
- Cosmic Ray H, He, & Electron (2.5,2)
- Gamma Ray Bursts (0.5, 1)
- UV Photometer (0.5, 0.5)
- Dust (1.5, 1.5)

	Mass (kg)	Power (W)
subtotal	25	23.5
DPU (Data Processing Unit)	2	1.5
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TOTAL	**27**	**25**
Goal	20	20

Analysis of the Heliopause Explorer desired dynamics has led to a design of trajectories with a three-leg scenario: 1) leave Earth, moving outwards beyond Earth's orbit to aphelions up to 2 AU, 2) turn back into the Sun to perihelions no less than 0.25 AU, and then 3) travel directly to interstellar space.

Trades with sail technology are useful to the mission/system designer. If the technology advances desired do not materialize in time for implementation, then mission performance sensitivity to the technology capability available is an important strategic planning metric. Figure 5 shows mission performance as a function of sail size and areal density (δ). It's clear from this plot that flight time is a significant driving parameter. Ten-year flight times will require relatively advanced sails (areal densities near 1 g/m^2) to keep the sail size down and payload mass reasonable. Relaxing the flight time will allow less advanced sails to deliver more massive payloads.

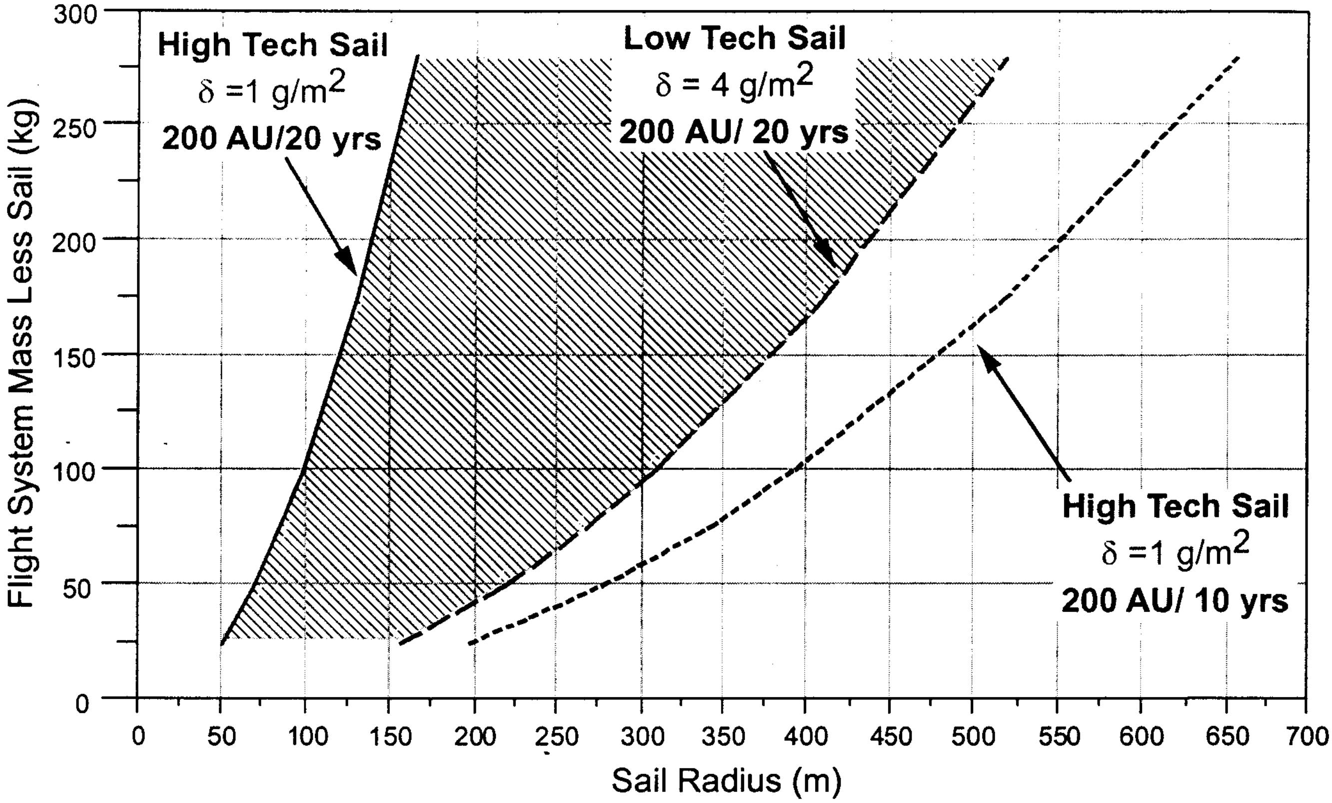

Figure 5. Heliopause Explorer Mission Performance as a Function of Solar Sail Size and Areal Density (δ)

Advanced Precursor Missions

Missions launching after Heliopause Explorer (> 2010) will require more than a simple solar sail can deliver in terms of mass and flight time. At this point (~ 2010) in our Interstellar Exploration roadmap (see Figure 2) a selection of one of the three advanced propulsion systems will be made, and the succeeding 2nd and 3rd Generation missions will be implemented with the selected advanced system. System definition awaits more study and research of these very advanced propulsion concepts.

5. Conclusions

Our ultimate vision for Interstellar Exploration awaits technology advances almost unimaginable at the present time. The preliminary roadmap for that visions does, however, suggest a path of exciting technology advances that will allow implementation of missions included in all of NASA's Space Science themes. The near-term advances are not daunting and will result in significant progress in NASA's goal of exploration.

The material presented here is the result of a few months of study at JPL. We see the overall milestones and general path to Interstellar Exploration. The nearer term details are clearer and can be implemented with modest resources. Indeed the technology community is already at work on the pieces required for early start. The overall program will need significant planning and coordination. Such an endeavor will require national effort, particularly in the research area of advanced propulsion.

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